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8 William Henry
from the Author

ON

DOUBLE IMAGES

CAUSED BY

ATMOSPHERICAL REFRACTION.

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BY

WILLIAM HYDE WOLLASTON, M.D. F.R.S.

FROM THE

PHILOSOPHICAL TRANSACTIONS.

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ON

DOUBLE IMAGES, &c.

Read before the ROYAL SOCIETY, *March* 6, 1800.

In some of the last volumes of the Philosophical Transactions, there have been related many instances of strong atmospherical refraction, by which, objects seen near the horizon have appeared inverted, and the horizon itself either elevated or depressed.

Mr. Huddart first took notice of a distinct image, inverted beneath the object itself; and, in the Philosophical Transactions for 1797, has described several such appearances, accompanied with an optical explanation, wherein he shews, that the lowest strata of the air were at the time endued with a weaker refractive power, than others at a small elevation.

In the volume for 1799, Mr. Vince has given an instance (Tab. I. Fig. 1.) where erect, as well as inverted images were visible above, instead of beneath, the objects themselves; and, by tracing the progress of the rays of light, in a manner similar to Mr. Huddart's, concludes that these phænomena arose

from "unusual variations" of increasing density in the lower strata of the atmosphere.

In the volume for 1795, Mr. DALBY mentions having seen "the top of a hill appear detached, for the sky was seen under "it." In this case, as well as in the preceding, it is probable that inversion took place, and that the lower half of the portion detached was an inverted image of the upper, as the sky could not be seen beneath it, but by an inverted course of the rays.

Since the causes of these peculiarities of terrestrial refraction have not received so full an explanation as might be wished, I have endeavoured,

1st. To investigate theoretically the successive variations of increasing or decreasing density to which fluids in general are liable, and the laws of the refractions occasioned by them.

2dly. To illustrate and confirm the truth of this theory, by experiments with fluids of known density.

And lastly, to ascertain, by trial upon the air itself, the causes and extent of those variations of its refractive density, on which the inversions of objects, and other phænomena observed, appear to depend.

The general laws may be comprised in three propositions.

Prop. 1. If the density of any medium varies by parallel indefinitely thin strata, any rays of light moving through it *in the direction of* the strata, will be made to deviate during their passage, and their deviations will be in proportion to the increments of density where they pass.

For each ray will be bent towards the denser strata, by a refracting force proportioned to the difference of the densities above and below the line of its passage; and, as their velocities are the same, and therefore the times of action of the forces

equal, the deviations will be as the refracting forces, *i. e.* as the increments of density.

Prop. II. When two fluids of unequal density are brought into contact, and unite by mutual penetration; if the densities at different heights be expressed by ordinates, the curve which terminates these ordinates will have a point of contrary flexure.

For the straight lines *da*, *rn*, (Plate IX.) Fig. 1. which terminate the ordinates *rx*, *dy*, of uniform density, will be parallel, and, if not united by contrary curvature, some straight line of union, as *ao*, must be supposed. But, from whatever cause the first line *ao* is inferred, by the same cause other intermediate lines *mp*, *tq*, *&c.* will be produced, and curves *defm*, *mtsr*, will be ultimately formed, having a point of contrary flexure at *m*.

The form of the curve does not appear to admit of accurate investigation, nor is it of importance to the subsequent reasoning, if wholly unknown. We may, however, form some judgment of its nature; for, whether the densities depend on different specific gravities of different fluids, or on unequal temperatures of different portions of the same fluid, the curves will be nearly alike.

In each of these cases, to whatever small distance *pc*, Fig. 2, the mutual attraction is sufficient to occasion intimate union of the fluids, the density *mn* of the mixture will be an arithmetic mean; and, for the same reason, at any intermediate smaller distances, there will be a series of arithmetic means *ef*, *gh*, *&c.* interposed, and the line *ao*, uniting the ordinates, will be straight.

By progressive effect of this attraction, and successive interpolations, in Fig. 1, curves *defm*, *rstm*, will be formed, of which the straight lines *mp*, *tq*, *&c.* are tangents.

The attracting distances *np*, *oq*, &c. are subtangents; and, if it be admitted that these are every where equal, the curves so produced are logarithmic, and the increment of the ordinate greatest at *m*, where they meet.

Prop. III. If parallel rays pass through a medium varying according to the preceding proposition, those above the point of contrary flexure will be made to diverge, and those below the same point will converge, after their passage through it.

For, since the deviation of each ray depends on the increment of density where it passes, and since the increment of density is greatest at the point of contrary flexure, any rays, as *ab*, Fig. 3, passing near to that point, will be refracted more towards the denser medium than those at *cd*, which move in a higher stratum, and will diverge from them, but will be refracted towards and meet those at *ef*, which pass nearer to the denser medium, where the increments of density are also less.

Cor. Hence, adjacent portions of the converging rays will form a focus, beyond which they will diverge again; and the varied medium will produce effects similar to those caused by a medium of uniform density* having a surface similar to the curve of densities, since convergence or divergence will be produced, according as the curve of densities is convex or concave; consequently, by tracing backwards, to the extremities of an

* In the varied medium, *bc* and *bm*, Fig. 4, the corresponding increments of the abscissa and ordinate, are to each other as radius to the tangent of the angle *c*. Therefore, the tangent of deviation, which is as the increment of the ordinate, varies as the tangent of the angle *c*.

So also, in the uniform medium, since the sines of refraction and incidence are in a given ratio, their differences will bear a given ratio to either of them; and, when the angles are small, the tangent of deviation will vary as the tangent of incidence, or as the tangent of the angle *c*, which is equal to it.

object, the progress of the visual rays, (or axes of the pencils received by the eye,) it will be manifest that,

Any object seen through the inclined concave part *rm*, Fig. 5. would appear elevated, erect, and somewhat diminished.

An object seen through *md*, where it is convex and inclined, would be elevated; and, if situated beyond the focus of visual rays from the eye, it would appear inverted. The magnitude would depend on the relative distances of the eye and object.

Below the point *d*, where the curve terminates, vision would be direct, so that an object might be situated so as to be seen in all three ways at the same time, direct at O, inverted at I, and erect again at A.

I consider the foregoing propositions as applicable to all cases of varying density, whether occasioned by mutual solution of different fluids, or partial rarefaction of the same fluid; and, by trial of various fluids, however different in density, or even in viscidity, I find that the refractions observe a law agreeable to the theory, as will appear by the following experiments.

Experiment 1. Into a square phial containing a small quantity of clear syrup, I put about an equal quantity of water, in such a way that it floated on the surface of the syrup, without mixing. For a short time, the stratum of union was so thin that nothing could be distinctly seen through it. But soon, by mutual penetration of the water and the syrup, the effects represented at A, Fig. 6, were produced.

Through the syrup, a word written on a card placed behind was seen erect, and in its place; through the adjacent variable medium, an inverted image was visible above the true place; and also, above that, a second image of the same object appeared erect.

When these appearances are first discernible, the variations of density are so great, that the object to be looked at may be in contact with the phial; but, when the variations of density become more gradual, and thereby the focus more distant, any object so near is only elongated, and requires to be removed an inch or two, to be seen inverted.

Exper. 2. Over the surface of the water, in the same phial, I next put about the same measure of rectified spirit of wine.

At the stratum where the water and spirit united, the appearances were the same; but, since the refractive power of spirit exceeds that of water, the true place of the object was seen uppermost; the inverted and erect images are below. Fig. 6, B.

When an oblique line *der* is viewed through any variable medium so made, it appears bent into different forms, according to its situation with respect to focal distance.

If it be at the distance of the principal focus, one point of it is dilated into a vertical line, as *lm*. Fig. 7, A.

If beyond that focus, the portion *lm* is inclined backwards, being an inverted image of *dl;* and *mn* is another image of the same portion seen erect. Fig. 7, B.

On this account, it becomes a convenient object for ascertaining the state of any medium under examination.

In these experiments, the appearances continue many hours, even with spirit of wine; with syrup, two or three days; with acid of vitriol, four or five; with a solution of gum arabic, much longer; but, although their disposition to unite is so different, the appearances produced are nevertheless the same in all.

The refraction is greatest nearly in the plain of original contact of the fluids, diminishing from thence both upwards and downwards. The exact rate of diminution above or below this

point, I had no means of measuring, with the accuracy that would be requisite for determining the nature of the curves of density formed according to the first proposition.

But the truth of the second proposition appeared capable of confirmation by experiment; for the deviation of a ray is there said to depend on the increment of density, and time of the ray's passage, jointly; accordingly, the deviation caused by a given increment should be in proportion to the extent of the medium.

In order to try what effect a greater extent of medium would produce,

Exper. 3. I made a rectangular glass vessel, of which the sides were in the ratio of 10 to 30,6; and, having put into it some clear syrup, with water on its surface, I measured the greatest refractions through it in both directions, and found them in the ratio of 10 to about 29.

In another vessel, of which the sides were as 10 to 40,4, the refractions were, on an average, as 1 to 4.

Being now fully satisfied of the effect of different fluids, I made the following experiment, whereby it appears, that the variations of density occasioned by difference of temperature between adjacent strata of the same fluid, follow a similar law.

Exper. 4. Having put some cold water into a square vessel, I covered its surface with a piece of writing paper perforated with a few small holes, and then filled the vessel cautiously with boiling water. The paper nearly prevented any mixture of the hot and cold water; but, by floating gradually up, left them to communicate their heat by contact alone.

While they were in this state, I examined the appearance of remote objects through the varied medium, and found, that

when my eye was removed four or five feet from the vessel, the effects were the same as in the preceding experiments with different fluids; above any object viewed through the cold water, I could distinguish two images of it, the one inverted, the other erect, as usual; but these appearances did not continue more than five or six minutes.

Having thus established, by experiments sufficiently varied, that the contiguity of two fluids of unequal density is capable of occasioning all the appearances that have been observed, I shall proceed to shew by what means the air may be made to exhibit similar phænomena.

Exper. 5. I heated a common poker red-hot, and held it so as to look along the side of it, at a paper 10 or 12 feet distant. The rarefaction occasioned by it caused a perceptible refraction, to the distance of about $\frac{3}{8}$ of an inch from the side of the poker. A letter seen more distant from it appeared as usual; within that distance there was a faint image of it reversed; and still nearer to the poker was a second image direct, and as distinct as the object itself, but somewhat smaller, as in Fig. 8, in which a section of the atmosphere surrounding the poker is represented. At the bottom and sides it is nearly circular; but upwards the circular form is lost in undulations, occasioned by the rapid ascent of the rarefied air.

The greatest deviation produced in this case measured about $\frac{1}{2}$ a degree.

Exper. 6. By a red-hot bar of iron, 30 inches long, the refractions were much greater, the extreme deviations amounting to full $1\frac{1}{4}$ degree.

The refractions observed in these experiments may, at first view, be thought greater than could be caused by difference of

temperature alone, being in one instance more than double the greatest horizontal refraction of the heavenly bodies; in which case, as the rays enter from a vacuum, the greatest possible effect of the atmosphere might be expected. But it must be remembered, that when a star appears in the horizon, its rays intersect the superior strata of the atmosphere at an inclination of several degrees, and that they pass but once through the variations from rarity to density; but, on the contrary, that in the experiments with red-hot iron, the rays may pass actually in the direction of the strata, and that they are refracted, not only by their entrance from the denser into the rarer medium, but the effect is doubled, since the refraction caused by their emergence is equal to that produced by their incidence.

Although a stratum of air, heated by these means to so great a degree, affords an erect, as well as an inverted, image of objects seen through it, the more moderate warmth communicated to it from bodies heated by the action of the sun upon them, seems insufficient to produce both images; but the inverted image may generally be seen, when the sun shines upon a brick wall, or other darker-coloured surface.

While the eye of the observer is placed nearly in a line with the wall, if another person, at 30 or 40 yards distance, extends any object towards the wall, an image similar to it will appear to come out to meet it.

It would be difficult to ascertain with accuracy the degree of rarefaction capable of shewing this appearance, but it may be of some use to future observers, to mention the different degrees of heat which I observed.

In one instance, a thermometer in contact with the wall, stood at 96°; but, at $\frac{3}{8}$ of an inch distance, 82°.

One morning, when the sun shone bright, I examined the temperatures and refraction produced at the surface of a deal bar painted green, about 8 feet long.

A small thermometer in contact with the bar, rose to 96°; at $\frac{1}{4}$ of an inch distance, it stood at 73°.

The refraction at the same time exceeded 20 minutes.

To explain why red-hot iron occasions two images, while solar heat produces but one, I imagine that the intense heat in the former case rarefies the air for some small distance uniformly, and thereby affords the same series of variations as between other fluids of uniform density; but that, in the latter, the heat is conveyed off as fast as it is generated; so that, as there is no extent of medium uniformly rare, the densities corresponding to the concave portion *rm*, Fig. 5. of the curve before described do not take place, but the phænomena occasioned by the convex part *md* are alone produced.

It must be remarked, that the vertical position of the surface contributes greatly to increase the effect; for, since the heated air rises in the direction of the surface, its ascent has in this case no tendency to blend it with the adjacent denser strata, and hence very different degrees of density take place in the thickness of $\frac{1}{4}$ of an inch; so that, as the increments of density are great, the refractions will be proportionally so; but, where the heated surface is horizontal, the ascent of the rarefied air into the superincumbent denser strata renders the variations far more gradual; consequently, a heated surface of far greater extent must be requisite, to produce equal refraction.

However, over extensive plains, when the sun shines, some degree of inversion is very frequently to be seen; but the inverted images are rarely well defined, unless over a very even

surface. One of the best situations for this purpose, is over a level open road, with a gentle breeze blowing across it. A current of air brings a cool stratum more closely in contact with the heated surface; and, since refraction depends on the increment or difference of density in a given small space, a very moderate breeze will thereby render inversion more perceptible; but a strong wind will reduce the temperature of the surface, and may make the heated stratum too thin for any object to be seen through it from a distance.

In one instance, when I saw a refraction of about 9 minutes, at the distance of $\frac{1}{3}$ of a mile, a thermometer in the sand was 101°; at 4 inches above, 82°; and, at 1 foot above, 76°.

Over water, the evenness of the surface is favourable to the production of such appearances; but, since the action of the sun is weak on a body so transparent, a far greater extent of surface is requisite to produce any perceptible inversion.

Being at Bognor one bright morning, when the sea was calm, I had an opportunity of observing the appearance of Selsea Bill, about 6 miles distant. The whole extent of coast, when viewed with a pocket telescope magnifying about 16 times, appeared inverted from one end to the other; and the lower part of a brick house upon the shore, was seen as distinct as the house itself. I judged the quantity of refraction, in this case, to be about 2 minutes of a degree.

This state of atmosphere appears to be not very uncommon; for, at Shanklin Chine, in the Isle of Wight, a few days preceding, similar appearances were visible in several directions, but I neglected to make any estimate of the quantity of refraction.

In the instance of the inverted vessel seen by Mr. HUDDART,

(Phil. Trans. for 1797, Tab. I. Fig. 3.) at the distance of 8 miles, the refraction seems to have been about 3′.

All the appearances described by him, I am inclined to think, arose from difference of temperature alone. He offers a conjecture, that evaporation might occasion the lower strata of the atmosphere to have a weaker refractive power; but, from the following experiments, it seems to have a contrary effect.

Exper. 7. I took a plate of glass, and, while I looked along the surface, I poured upon it a small quantity of ether.

A line upon the opposite wall, appeared instantaneously elevated many minutes, and at times above ½ a degree.

This fluid being the most volatile, and most soluble in the atmosphere, of any known liquid, produces the greatest effect; since the cold, during evaporation, conspires with the ether dissolved in the air, to increase the refractive power.

Rectified spirit of wine also produces, from the same cause, a very considerable effect.

Exper. 8. By moistening a board, 5 feet in length, with alcohol, and observing the elevation of an object viewed over its surface, I found the refraction to be about 15′.

Exper. 9. I next made a similar experiment with water itself. Of this, the effect was barely visible, when tried in the same way; but, by means of a surface of 10 feet, and by viewing a luminous point at a greater distance, the refraction became evident, and the object elevated above 3 minutes.

In the course of these experiments, I tried whether confining the saturated atmosphere, by boards on each side, would vary the effect, and found the refraction in all cases much lessened; and, when water was used, it became imperceptible; but, as soon as the boards were removed, and a free current allowed to

pass across, the full effect was again produced. The reason of this difference appears to be, that the quicker evaporation increases the degree of cold, and the current brings greater differences of density contiguous.

This state of rapid evaporation will fully account for the phænomenon witnessed by Mr. LATHAM, who has described (in the Phil. Trans. for 1796, p. 357) an extraordinary elevation of the opposite coast of France, so as to be seen from the beach at Hastings, and other parts of Sussex.

There is a fact of the same kind stated by DE LA LANDE, (*Astron.* Tom. II.) who says that the mountains of Corsica (though at the distance of more than 100 miles) are occasionally visible from Genoa.

It is probably owing to the same cause, that other objects have been sometimes seen, at such distances that we should expect them to be intercepted by the curvature of the earth; for it is evident, that whensoever the evaporation over each mile of surface occasions a refraction of about 1 minute, the rays receive a curvature equal to that of the ocean, so that its surface will appear flat, and the spherical form of the earth will not obstruct horizontal vision of objects at any distance.

It still remained to explain the phænomena seen by Mr. VINCE, as I had not hitherto made an atmosphere capable of exhibiting images inverted, as well as elevated, by increased density. For, in the refractions produced in the 7th, 8th, and 9th experiments, by evaporation at an exposed surface, I observed the effect was always greatest in contact with the evaporating surface; any lower point *a*, Fig. 9, appeared brought nearer to a higher point *c*, by the pencil of rays from *a* being more refracted at *b*, than the pencil from *c* was refracted at *d*. Therefore, any rays passing from the eye at *e*, as a point, through

b and *d*, would be made to diverge to *a* and *c*; consequently, visual rays could not, under these circumstances, intersect each other, and no objects could appear inverted.

But, whenever the lowest strata of the air become saturated with moisture, the variations between the saturated stratum and the incumbent atmosphere of the common density, will follow a law similar to what is found at the confines of other fluids of unequal density; hence, inversion will become visible, as there will be a point below which the increment of density will decrease, and where the refractions will consequently be less, although through a denser medium.

Exper. 10. To produce these appearances, I procured a trough of thin deal, 5 feet long, 1 inch wide, with sides $2\frac{1}{2}$ inches high, and closed the extremities of it with glass. A section of it is given in Fig. 10.

When the bottom was wetted with ether, the greatest refraction was, at intervals, more than $\frac{3}{4}$ of an inch from the bottom of the trough; and, beneath this height, I saw a second image inverted, when my eye was removed to 14 or 15 feet distance, and the object at about 70 feet. The focus seemed at the same time to be about 9 feet distant.

There was not depth enough of uniformly saturated atmosphere for the object itself to be seen through it, but its true place, compared with that of the images, is represented at *a*.

Exper. 11. When I made use of rectified spirit in the same apparatus, I had also sufficient proof that the laws of evaporation would admit of such appearances being produced; for the same object now appeared curved downwards, as in Fig. 11, so that rays nearer to the bottom were manifestly less refracted than such as passed at some distance above. A degree of convergency must therefore have been produced, although the dis-

tance at which the rays would meet, was beyond that of my eye, and circumstances would not admit of my removing beyond 35 feet.

The evaporation of water could not be expected to produce any sensible effect of this kind, in so short a space; but, in a view of some miles extent, there can be no doubt, from the foregoing experiments, that evaporation from the surface of the sea, in such a state of the atmosphere as would allow the lower strata to be saturated, is capable of occasioning all the phænomena which have been described, and probably was the cause of those which Mr. VINCE observed.

Since heat alone tends to depress objects, and evaporation produces apparent elevation, it is probable, that in the instance of refraction related by Mr. DALBY, (Phil. Trans. for 1795, p. 587), the heat of the sun was the principal agent, and that the moisture rather tended to counteract than assist its action.

Simple inversion may generally be seen, when the sun shines upon a *dry* even road of $\frac{1}{3}$ or $\frac{1}{2}$ mile extent; but, when the ground has been wet, I have very rarely seen it, and have even failed of discerning it, when the heat has been sufficient to raise a steam from the ground.

The following experiment shews that it is not to be expected but by very great extent of surface.

Exper. 12. I placed a dark-coloured board in the sunshine, and, having examined the refraction along its surface, I made a wet line along it, with a sponge dipped in boiling water. Notwithstanding this additional heat, the refraction, in the direction of the wet line, was far less than over the rest of the board, although I took care to observe the effect, before the surface could be cooled again by evaporation.

I should therefore expect the depression of the horizon at sea,

where the refraction occasioned by heat must always be counteracted by evaporation, never to exceed a few minutes; and that any one in a situation commanding a view of the sea, by attention to the various degrees of the dip of the horizon under different circumstances, might soon form some estimate of the proper allowance to be made, for brightness of the sun at the time of an astronomical observation, or for difference of temperature between the sea and air.

Having now examined the several peculiarities of refraction which I proposed for consideration, I shall, in few words, recapitulate the purport of the foregoing pages.

According to the theory here given, there appear to be two opposite states of the atmosphere, either of which may occasion objects to be seen doubled or tripled, since both increase and decrease of its density, when partial, produce similar effects.

It has been explained,

1st. Why air heated by the moderate warmth of the sun's rays, occasions objects to appear doubled and inverted.

2dly. Why rarefaction, by a higher degree of heat, gives an additional image, which is not inverted.

3dly. In what state of evaporation the increase of the air's density brings distant objects into view by unusual elevation.

4thly. Under what circumstances evaporation may also produce an inverted image less elevated.

And it is probable, that the same reasoning will afford a ready explanation to other varieties of terrestrial refraction, that may have been, or may hereafter be observed.

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Fig. 1.

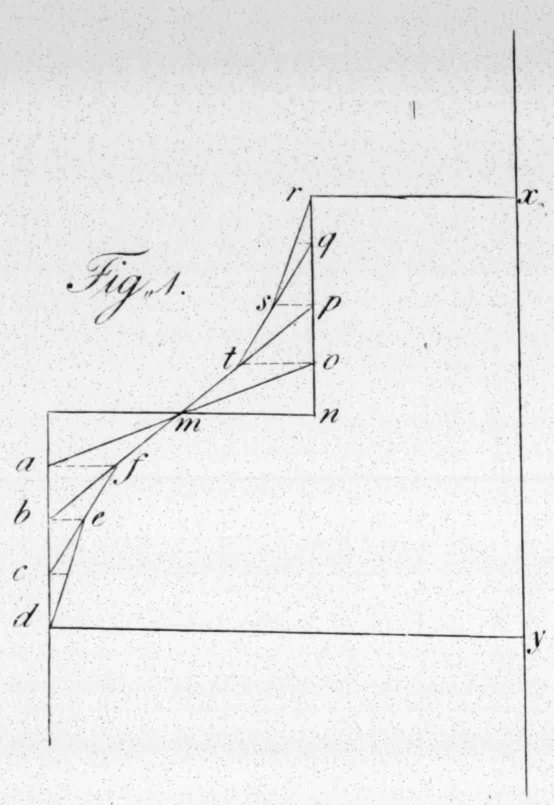
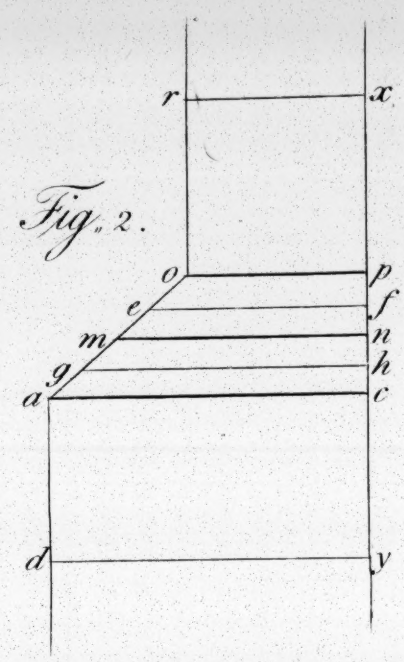


Fig. 2.



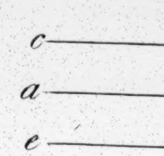


Fig. 5.

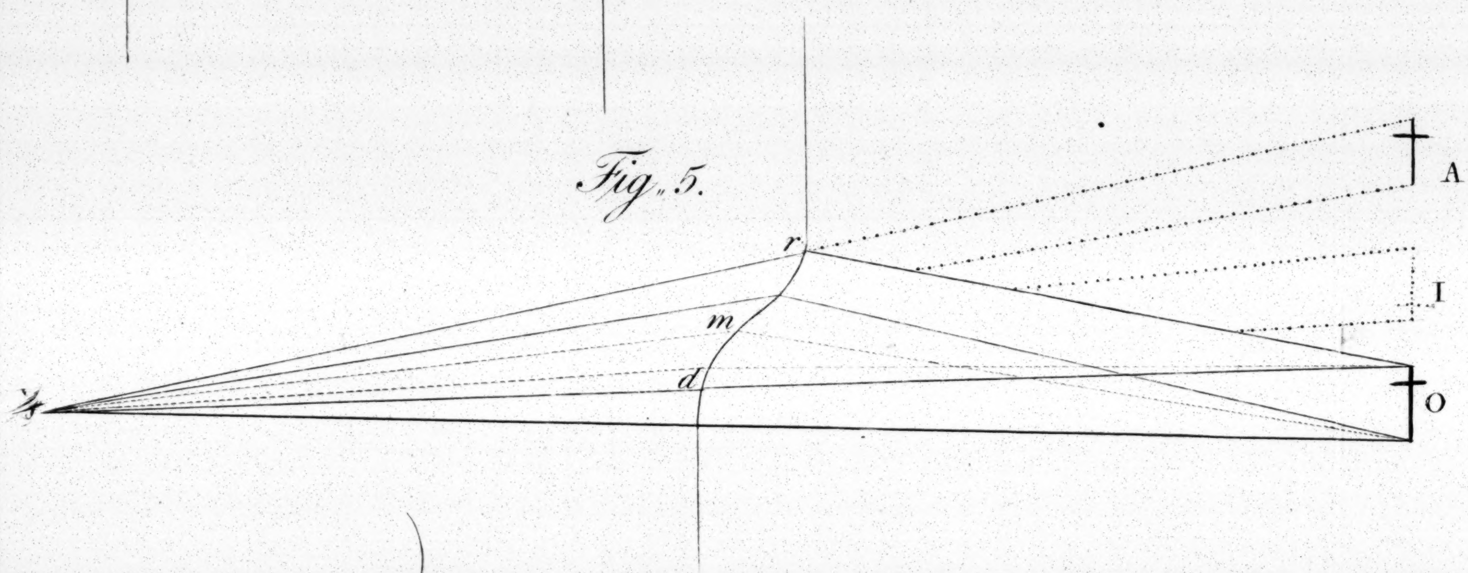


Fig. 8.

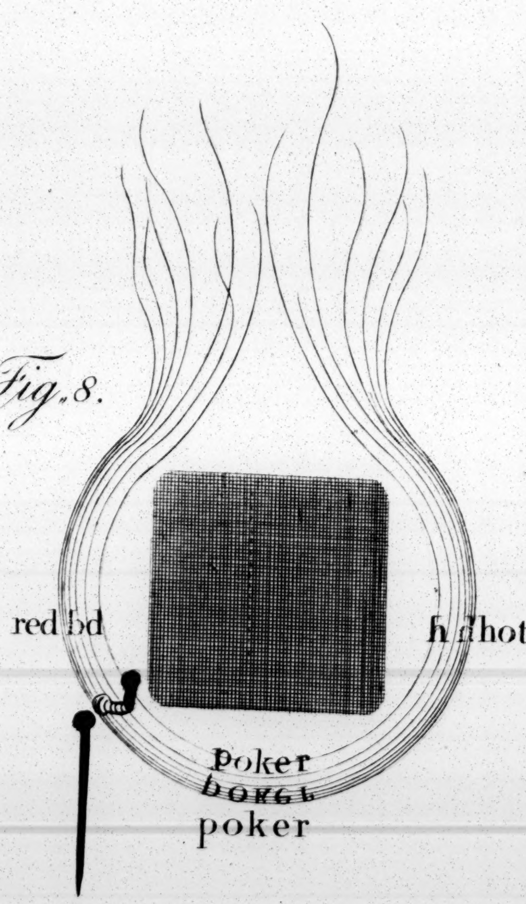


Fig. 9.

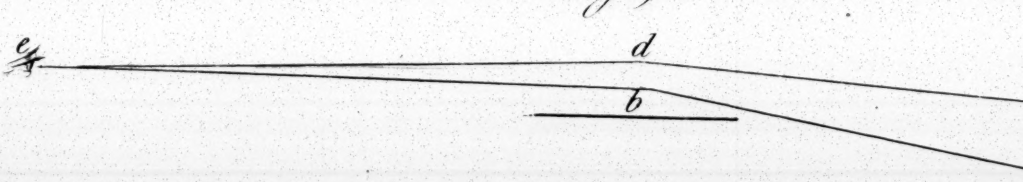


Fig. 3.

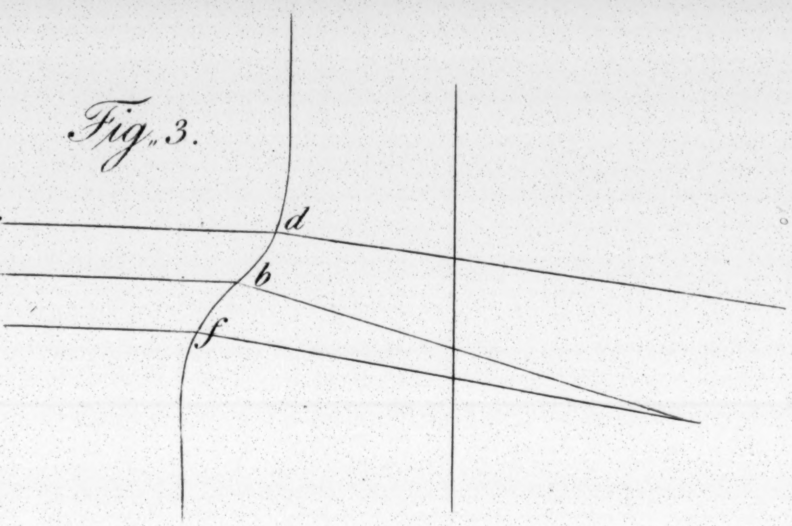


Fig. 4.

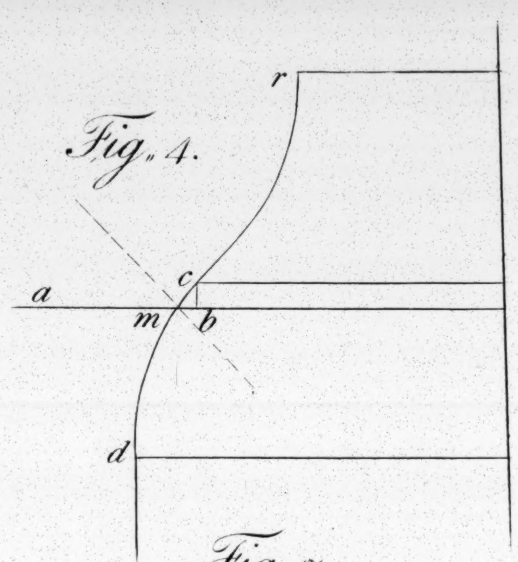


Fig. 6.

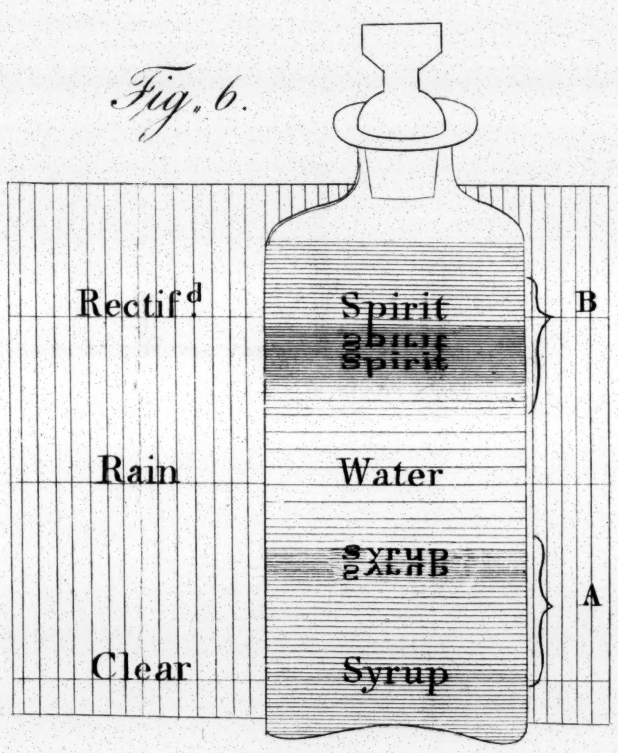


Fig. 7.

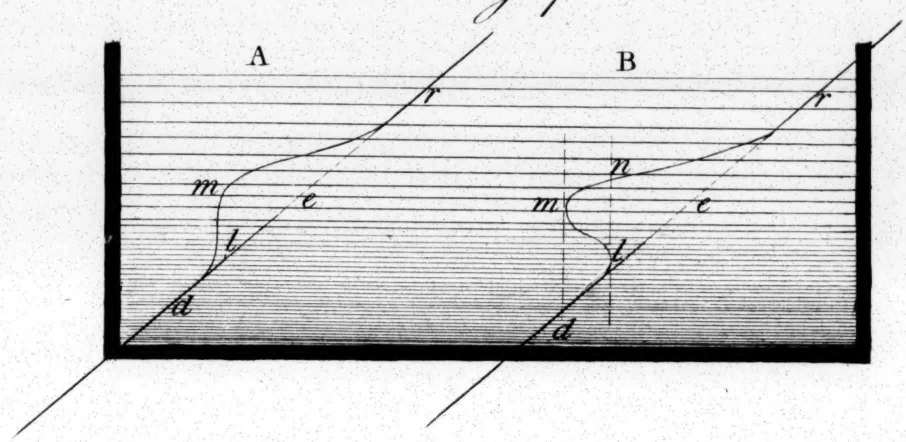


Fig 10.

Fig. 11.